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Gamma-Ray Constraints on the Galactic Supernova Rate

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Abstract

Most Galactic supernovae are hidden from our view due to severe extinction in the Galactic plane. In the γ-ray band the Galaxy is almost transparent so that we could detect supernovae that are obscured. ^{44}Ti is among the potentially detectable isotopes in supernova ejecta. Surveys carried out with the HEAO 3 experiment and γ-ray detectors aboard the Solar Maximum Mission (SMM) have not detected γ-ray lines expected from the decay chain $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$. These observations thus constrain the rates and nucleosynthesis of supernovae. We perform Monte Carlo simulations of the expected γ-ray signatures of Galactic supernovae of all types to estimate the significance of the lack of a γ-ray signal due to supernovae occuring during the last millenium. Using recent estimates of the nuclear yields we determine mean Galactic supernova rates consistent with the historic supernova record and the γ-ray limits. Another objective of these calculations of Galactic supernova histories is their application to surveys of diffuse Galactic γ-ray line emission.

1 Introduction

Detection of γ-ray line emission from ongoing Galactic nucleosynthesis is one of the major observational goals of γ-ray astronomy. We consider the signal from the decay $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$. Measurements of the ^{44}Ti half-life prior to 1965 implied $t_{1/2} \leq 50$ years, but recent Brookhaven measurements suggest a much longer half-life of 66.6 years (Adelberger & Harbottle 1990). Here we adopt the intermediate half-life of 54.2 years (Frekers *et al.* 1983), corresponding to $\tau = 78.2$ years, which was also employed by Mahoney *et al.* (1991). Pinning down the correct value remains an important objective in nuclear astrophysics. Because of this short life-time, detection of a γ-ray signal from ^{44}Ti involves either very recent or very near supernovae.

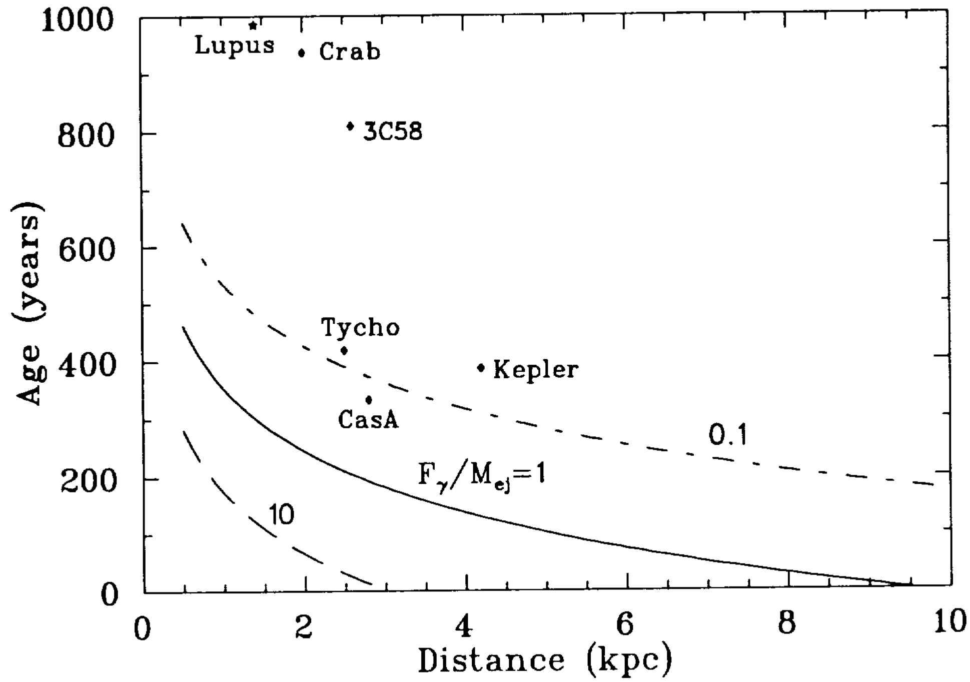

Figure 1: *Age distance relationship for γ-ray line emission from ^{44}Ti. Source detectability depends on the ratio of flux limit to ejected mass, F_γ/M_{ej}. Six historic supernovae are shown.*

The decay of ^{44}Ti generates three γ-ray photons with energies of 78.4 keV, 67.9 keV, and 1.157 MeV. The resulting line flux at earth is

$$F_\gamma \sim 1 \times 10^{-2}\ M_{-4}\ \exp(-t/78.2\ \mathrm{yrs})\ D^{-2}(kpc)\ \ \mathrm{photons\ cm^{-2}s^{-1}}\ ,$$

where M_{-4} is the ejected ^{44}Ti mass in units of 10^{-4} $M_\odot$ The detectability of such emission from recent supernovae in our Galaxy and perhaps from a few older but nearby remnants make this nucleus a prime γ-ray target (Figure 1). It is clear, however, that the search for ^{44}Ti line emission from previously undetected Galactic supernovae deals with the few events of the past couple of centuries, so that the interpretation of line detection, or lack thereof, is statistical in nature. This is similar to the situation of ^{22}Na, and our Monte Carlo analysis is conducted in the spirit of Higdon and Fowler's (1987) analysis of ^{22}Na detectability from novae.

Searches for ^{44}Ti line emission have been carried out using the high-resolution γ-ray spectroscopy experiment on HEAO 3 (Mahoney *et al.* 1991) and the γ-ray spectrometer aboard the SMM satellite (Leising & Share 1991). No signal was detected with either instrument. Mahoney *et al.* (1991) used the HEAO 3 limit to constrain the combination of supernova rate and mass of ^{44}Ti ejected per event, but considered the relevant supernovae to be of Type Ia and ignored constraints from the optical signature of these events. Current nucleosynthesis estimates for ^{44}Ti suggest that in fact supernovae involving massive stars (Type Ib and II) may dominate the production of this isotope. We take a somewhat different approach and utilize current yield estimates (and their uncertainties) to constrain exclusively the mean Galactic supernova rate.

2 Yields and Sites

To achieve full solar production of ^{57}Fe and ^{44}Ca their γ-ray emitting progenitors ^{57}Ni and ^{44}Ti must be produced in environments that guarantee a significant contribution from the so called "alpha-rich freeze-out" (Woosley, Arnett, & Clayton 1973). This component can be expected when low density matter falls out of nuclear statistical equilibrium (NSE) while being cooled so rapidly that free alpha particles have insufficient time to reassemble back into more massive nuclei. In contrast to normal freezeout from NSE at high densities, the large mass fraction of surviving alpha particles drastically alters the resulting nucleosynthesis. It is generally believed that alpha-rich freeze-out must be invoked to explain solar abundances of several isotopes, including ^{57}Fe, ^{59}Co, ^{58,60,61,62}Ni, and ^{64}Zn (Woosley 1986). We utilize the fact that the synthesis of ^{44}Ti and ^{57}Ni occurs in similar, if not the same, astrophysical sites, and take advantage of observations of SN 1987A to estimate ^{44}Ti yields. Mahoney *et al.* (1991) treated the titanium yield as a free parameter and assumed it to be the same for all events.

The bolometric luminosity of SN 1987A at late times is dominated by the radioactivity of ^{44}Ti (e.g., Woosley, Pinto, & Hartmann 1989). The abundance of ^{44}Ti is sensitive to pre-explosive details of stellar evolution as well as the explosion mechanism. For SN 1987A Kumagai *et al.* (1989) and Woosley & Pinto (1988) estimate Ti production near 10^{-4} $M_\odot$. This result is uncertain by at least a factor of two. Parametrized nucleosynthesis studies (Woosley & Hoffman 1991: WH) can also be used to constrain production of ^{44}Ti. Assuming that ^{56}Ni is the dominant constituent of iron group elements ejected in SNII and using a conservative lower limit on the neutron enrichment parameter $\eta \lesssim 10^{-3}$, the parametrized synthesis calculations constrain the ratio $r_{57} = X(^{57}\mathrm{Ni})/X(^{56}\mathrm{Ni})$. To avoid overproduction of ^{58}Ni by a factor of 5 or more, WH finds $r_{57} \lesssim 2r_{57\odot}$. The lower limit on η corresponds to a lower limit $r_{57} \gtrsim 0.3$ $r_{57\odot}$ in the case that an α-rich freeze-out does not occur. For the most realistic η values and a modest α-rich freeze-out WH find $r_{57} \gtrsim 0.7\ r_{57\odot}$.

Production of ^{44}Ti and ^{57}Co is dominated by stellar zones that have experienced some alpha-rich freeze-out. Thus, the limits on ^{57}Co also provide a constraint on the ^{44}Ti yields. WH find that a Ti production ratio $P_{44} = {}^{44}\mathrm{Ti}/{}^{56}\mathrm{Fe}$ close to solar ($P_{44\odot} \sim 1.2\times10^{-3}$) occurs for a variety of conditions and that the upper limit on r_{57} restricts P_{44} to less than twice solar. Recent observations of the bolometric light curve of SN 1987A suggest $r_{57} \sim 5$ (Suntzeff *et al.* 1991), which implies copious co-production of ^{44}Ti ($P_{44} \sim 2P_{44\odot}$) in Type II supernovae, but the uncertainties in modeling the bolometric lightcurve are still very large. Dynamic simulations of explosive nucleosynthesis (Hashimoto *et al.* 1989; Kumagai *et al.* 1989; Woosley, Pinto, & Weaver 1988; Woosley 1991) estimate $P_{44} \sim 1.5-2.5\ P_{44\odot}$, so that a typical Type II supernova might eject $10^{-4} M_\odot$. However, these simulations are not yet realistic, because they assume either a piston or instantaneous energy deposition. We randomly select the ejected ^{44}Ti mass in SNII from $M_{\mathrm{ej}} \sim\ \zeta\ P_{44\odot}\ M_{56}$, where ζ is randomly chosen between 0.5 and 2.0, and the ejected mass of ^{56}Fe varies between $2\times10^{-3} M_\odot$ and 0.3 $M_\odot$ for stars with initial mass between 10 $M_\odot$ and 35 $M_\odot$. The initial mass was selected from a Salpeter IMF by another random number. The same prescription is used for SNIb, but the amount of ejected ^{56}Fe is kept fixed at 0.3 $M_\odot$, because not enough SNIb have been observed to estimate their intrinsic spread in iron production. For SNIa we randomly draw an ejected iron mass between 0.25 $M_\odot$ and 0.75 $M_\odot$, and select ζ between 0.03 and 0.08. The titanium synthesis in these exploding carbon-oxygen white dwarfs is not very well known, but recent models of delayed detonations (DD) support the ζ range employed here. In DD models of Type Ia supernovae substantial production of intermediate mass isotopes (O, Mg, Si, Ca..) occurs because the detonation wave propagates through low density matter in the pre-expanded white dwarf envelope. Estimates of the yields of isotopes in this mass range are sensitive to the uncertain transition density where the initial deflagration turns into a detonation.

The rate of SNIa is about a factor 10 smaller than that of supernovae involving massive stars (Ib & II). Thus, the Galactic nucleosynthesis of ^{44}Ti could be dominated by SNII and SNIb, but from the point of view of γ-ray searches for individual Galactic events only the product $\zeta P_{44\odot}\ M_{56}$ matters. Although uncertain, the values discussed above clearly indicate that one must include all supernova classes in the analysis.

3 Event Distribution

3.1 Spatial Distributions

The standard scenarios for Type Ia supernovae involve accreting white dwarfs, which motivates the use of distribution models derived for novae (Higdon & Fowler 1987; Mahoney *et al.* 1991). The Galactic nova distribution is not well known because of severe extinction corrections. To alleviate this problem one relies on nova surveys of M31 where sample completeness is much higher (e.g., Ciardullo *et al.* 1987). From these observations one expects contributions from two distinct populations: disk and spheroid. We follow Higdon & Fowler (1987) who generate Monte Carlo representations of these populations from integral probability distributions for an axisymmetric disk and a spherically symmetric bulge component. The observations of M31 seem to suggest that the nova rate traces the blue light distribution. Using the Bahcall-Soneira Galaxy model Mahoney *et al.* (1991) argue that the fraction of SNIa occuring in the spheroid is about 1/6. The remaining two classes of events are thought to be associated with massive stars and thus follow a Pop I spatial distribution. We assume that birth places are exponentially distributed in height above the plane with a scale length of 100 pc. Ignoring spiral structure we assume smooth radial birth functions that are either constant within some radius σ_r, fall off exponentially with distance from the Galactic center (with scale length σ_r), or are ring-like $\rho(r) \propto \exp\left((r-r_0)^2/\sigma_r^2\right)$, where H_2 observations suggest that $r_0 \sim 5$ kpc.

3.2 Supernova Rates

Instead of treating the total Galactic rate of each supernova class as a free parameter, we fix the relative rates based on observations of external galaxies and vary the total rate. Relative supernova rates are sensitive to the type of the host galaxy (e.g., Tammann 1991). The Hubble type of the Milky Way is not accurately known, but is most likely between Sbc and Sd, so that the observations suggest the following breakdown (Ia:Ib:II) = (1:1.6:8) (Tammann 1991). We thus assume that a fraction $F_{Ia} \sim 0.09$ of all events is of type Ia. Similarly, the fraction of type Ib events among supernovae involving massive stars is $F_{Ib} \sim 0.16$. These values are used to randomly assign an event class.

4 Optical Constraints

4.1 The Historic Record

Supernovae are rare events in our Galaxy, only six are known to have occured during the last millenium. Without doubt, additional supernovae occured during that period but were not observed because of obscuration by interstellar matter. Still, we can use these historic events to constrain the range of acceptable mean Galactic supernova rates. Classification and peak magnitudes of historic events are uncertain, but we follow van den Bergh (1990) for the breakdown (Ia:Ib:II) $\sim$ (1:2:3). All of these events were brighter than $m_V = 0$. We assume that the historic record is complete above this level. On the other hand, the record of historic nova discoveries above the same limit suggests a rather strong time dependence, suggesting that the historic supernova record could be very incomplete as well (van den Bergh & Tammann 1991; van den Bergh 1991b; Tammann 1991). We allow for a factor 2 in all of the above numbers, so that there could have been a total of 12 detectable events.

Within about 4 kpc of the sun there were between 3 and 4 core collapse supernovae. From a comparison of the total Galactic Pop I content to that within a cylinder of that radius Ratnatunga and van den Bergh (1989) infer that the total Galactic core collapse rate is of order 6-8 events per century. This value is well above theoretical estimates based on integrating a reasonable IMF (van den Bergh 1991a) or values derived from extragalactic evidence (Evans, van den Bergh & McClure 1989) that give $\sim 2.2 \pm 2$ and 2.6 ± 0.7, respectively. This problem of an unexpectedly high apparent frequency of nearby supernovae has been discussed in detail by van den Bergh (1990). A supernova rate as high as 1/10 yrs requires a star formation rate that exhausts the available gas supply in the Galactic annulus of the solar neighborhood in less than $\sim 10^9$ yrs (van den Bergh 1991b). This is inconsistent with age estimates of the Galactic disk ($T_d \sim 10^{10}$ yrs) derived from white dwarf luminosity functions. We consider the possibility that the actual mean supernova rate is in fact as low as indicated by extragalactic observations and that the observed large number of local supernovae during the past millenium is just a statistical fluctuation.

4.2 Peak Magnitudes

Observations suggest that the absolute magnitude in the B-band for Type Ia supernovae is so well defined that we can use SNIa as standard candles (e.g., Leibundgut 1991; Branch & Tammann 1991). We follow Leibundgut and Tammann (1990) by employing $M_B(max) = -18.3 + 5\ log(h)$, where h is the Hubble constant normalized to 100 km/s/Mpc. Furthermore, the observations suggest that B-V $\sim$ 0 at maximum light. Throughout this paper we assume h=1. Supernovae of Type Ib are fainter than SNIa (e.g., Porter and Filipenko 1987). Because of its recent establishment as an independent class, too few events have been studied well enough to determine accurately their peak magnitude and intrinsic spread. We therefore assume a single value (Evans, van den Bergh, & McClure 1989) $M_B(max) = -16.7 + 5\ log(h)$. Still fainter at peak than SNIb's are Type II supernovae. We follow Tammann & Schröder (1990) and use $M_B(max) = -15.7 + 5\ log(h)$. To include the possibility of underluminous SNII, such as 1987A, we add uniform random fluctuations with amplitude $\delta M_B = 1.2$ mag. Tammann & Schröder (1990) use a Gaussian distribution that rarely gives such underluminous events, although these events could be common (e.g., Branch 1990; Schmitz & Gaskell 1988).

4.3 Extinction

Galaxy counts and photometric studies of stellar reddening at high Galactic latitudes imply a polar photographic extinction A_{ph} of about 0.25 mag or less than 0.1 mag, respectively (Heiles 1976; Burstein & McDonald 1975). However, a careful re-analysis of galaxy counts (Burstein & Heiles 1978) has shown that these data are too noisy to distinguish between zero extinction and a csc(b) law with an amplitude of 0.25 mag. The study by Burstein and Heiles also showed that a smooth csc(b) law does not give a good representation of extinction because of the patchiness in the interstellar dust component.

From the more reliable photometric studies of stars and globular clusters it appears that the extinction toward the galactic poles is of order of 0.2 mag or less. An extinction of 1 mag corresponds roughly to a hydrogen column density along the line of sight of N(HI) = 10^{21} cm^{-2} (Burstein and Heiles 1978). Extinction and optical depth, τ, at some wavelength are related by $A_\lambda = 1.086\ \tau_\lambda$. Although there still is considerable debate about the correct value of the polar extinction, the average optical depth of the half disk in spiral galaxies is commonly assumed to be of order $\tau_p = 0.2$ (e.g., Sandage and Tammann 1981). However, the question whether galaxy disks are optically thin or opaque is still debated (e.g., Disney, Davies, and Phillips 1989; Valentijn 1990). Because the radial scale length of the Galaxy is so much larger than the vertical scale height of the dust layer (which produces the bulk of the extinction) a total optical depth to the Galactic center may be as high as $\tau_c \sim 40$. In the solar neighborhood the average extinction per unit length is of order $\tau_a = 1$ kpc^{-1} (Mihalas and Binney 1981).

We employ simple extinction models that assume either constant, exponentially decaying, or ring-like density distributions with respect to galactocentric radius and that are either constant, exponentially decaying, or Gaussian with respect to the height above the Galactic plane. We normalize the resulting density distribution such that the polar optical depth is exactly equal to $\tau_p = 0.2$. To determine the extinction correction for a particular event in the Galaxy we first integrate along the line of sight and then add a maximally 50% correction, reflecting the patchiness of the ISM, by $\tau_{eff} = \tau(D)\ (1 - (r - 1/2)\exp(-\tau(D))$, where r is a uniform random variable between 0 and 1. The exponential factor reduces the fluctuations for observations of objects with large intervening column depths. After applying extinction corrections we consider a supernova optically detected when its apparent magnitude is brighter than m_v=0.

4.4 Results and Conclusions

Because of the short life time of ^{44}Ti the γ-ray glow of our Galaxy is expected to be dominated by perhaps a few recent events. However, as Figure 1 shows, none of the known historic supernovae is either close or young (or both) enough to be detectable in the "titanium window" (assuming standard yields). Thus one searches for emission from recent supernovae that remained unrecognized due to either Galactic absorption or gaps in sky coverage during the past millenium.

Mahoney *et al.* (1991) searched through the scan-by-scan data of the HEAO 3 γ-ray experiment. Of the three γ-ray lines associated with the decay of ^{44}Ti emission at 68.9 keV and 78.4 keV is most easily detectable by the HEAO 3 spectrometer. Mahoney *et al.* (1991) searched for flux enhancements in 16 channels covering the energy range 58–90 keV. The high-resolution spectrometer aboard HEAO 3 scanned the sky with a field of view of $\sim 30°$ and a period of about 20 minutes. Mahoney *et al.* (1991) analyzed the scans, searching for a point source at a

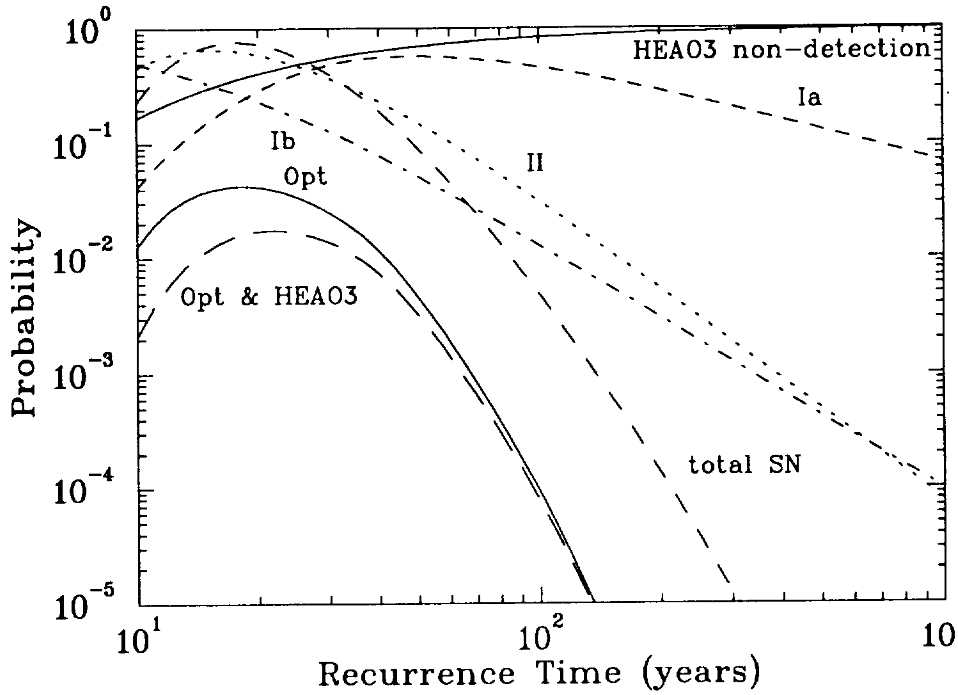

Figure 2: *Optical and γ-ray probabilities using the HEAO 3 flux limit.*

given location on the sky whose flux is modulated by the time dependent instrument response. Hypothetical point sources were assumed to be spaced 10° apart in Galactic longitude to assure maximum instrumental sensitivity. None of the resulting 36 bins along the Galactic plane showed any significant flux enhancement. HEAO 3 would have detected a source line flux of $\sim 2\times10^{-4}$ photons / cm^2 s about 99% of the time. This limit is used in this study.

Leising and Share (1991) have searched nearly ten years of data from NASA's Solar Maximum Mission (SMM) Gamma-Ray Spectrometer for evidence of γ-ray line emission from the decay of ^{44}Ti. They modeled the expected signals resulting from the annual scan of the ecliptic by SMM, considering point sources of various individual undiscovered events which might eject ^{44}Ti. They find no evidence of Galactic emission from ^{44}Ti, and find 99% confidence limits of 10^{-4} photons cm^{-2} s^{-1} for the 1.16 MeV line from ^{44}Sc from arbitrary points near the Galactic center. The limits on 1.16 MeV flux from longitudes near ± 90° rise to 2×10^{-4} cm^{-2} s^{-1} due to the reduced sensitivity in those directions.

Using the previously described procedures for randomly generating Galactic supernova events of all types, we perform a sufficient number of Monte Carlo simulations to determine the probabilities for detection of these events in the γ-ray band and the optical band. For a given average supernova rate in the Galaxy one can then analytically calculate the total probabilities for such histories to be consistent with the observed historic supernova record and the lack of γ-ray detections. Figure 2 shows a typical Monte Carlo result for a specific model of yields, extinction, relative SN frequencies, etc. The full curve "Opt" gives the probability that a history satisfies simultaneously the historic limits of each supernova type (i.e., 1-2 Ia; 2-4 Ib; 3-6 II). Individual probabilities are also shown. The dashed curve "total SN" gives the

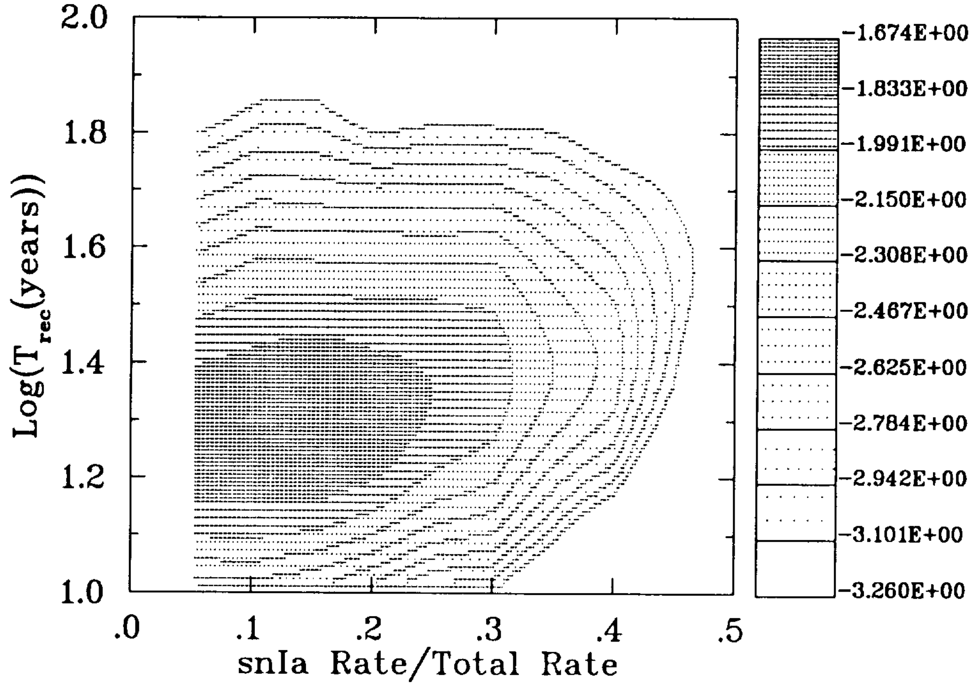

Figure 3: *Contours of combined optical and γ-ray probabilities as a function of total supernova rate and ratio Ia/(Ia+Ib+II). The labels give the logarithm of the joint probability for model histories to match the supernova record and to avoid HEAO 3 γ-ray detection.*

probability for the total number of SNe to be within the historic range (6-12), independent of type. The upper solid curve gives the probability for non-detection of γ-rays using the HEAO-3 limit. The lower dashed curve ("Opt&HEAO3") is the total combined probability for a model to satisfy both optical and γ-ray constraints. Based on optical data alone, the particular model shown in Figure 2 has a most likely supernova recurrence time of $\sim$ 18 years and the observed Galactic historic record is reproduced in about 4% of all Monte Carlo histories (this is still an acceptable model for Galactic supernova histories). Recurrence rates as short as 10 years yield only a 7% probability for non-detection of ^{44}Ti γ-ray lines. The combined optical/γ-ray model is thus severely constrained on the high frequency side, resulting in a most likely recurrence time of $\sim$ 23 years with peak probability to match both data sets of 1%. This model is thus still acceptable. Varying the total supernova rate and the ratio Ia/(Ia+Ib+II), we perform Monte Carlo simulations to determine the extent of the acceptable parameter space in which the combined probabilities exceed, say, 1%. The results (Figure 3) are fully consistent with those derived from extragalactic supernova searches, but we emphasize that γ-ray constraints on the recurrence times clearly rule out supernova frequencies as high as 1/10 years.

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